

Natural Etching and Annealing of Zircons : An Evidence Based on Fission Track Ages of Samples from Ikuno Ore Field, Southwest Japan*

Nghiem Vu KHAI and WADATSUMI Kiyoshi

(With 2 Tables and 8 Figures)

Abstract

The fission track (FT) ages of zircon samples from the Kanagase polymetallic ore vein and its contact zone have been determined for both 4π -geometry (4π) and 2π -geometry (2π) surfaces, using External Detector Method (EDM).

The 4π FT and 2π FT age data of the samples, arranged in an orderly manner from near contact zone outward into the host rocks (IK1 and IK3, IK5, IK6, IK2) are: 55-91 Ma, 60-77 Ma, 60-81 Ma, 62-76 Ma, respectively. Thus the 2π ages are consistently older than 4π ones and two contrasting tendencies can be observed: a) 4π ages decrease toward the ore vein, b) 2π ages show an inverse tendency; i.e., they are decreasing from the vein outward for a limited distance.

The decrease in 4π ages is probably due to natural annealing of spontaneous tracks in zircon crystals during a high temperature ore forming stage. The 2π ages reflect the combined result of both natural etching and annealing of the tracks on zircon crystal surfaces. It means that the tracks underwent natural etching during pre-ore hydrothermal alteration, before annealing process took place, so that the etched tracks could not be annealed effectively. Closer to ore fluids channel both natural annealing and etching rates are higher and they decrease with distance from the vein.

This model demonstrates a real difference between 4π and 2π FT ages obtained for the samples and indicates that careful consideration is needed before interpreting their geological meaning.

1. Introduction

Fission track analysis, based on natural decay by spontaneous fission of the U^{238} , has found increasing application in various fields of geochronology, including thermochronological studies. Thermochronological studies deal with the time-temperature history of the geological processes of the Earth's crust. It is well known that when the ambient temperature reaches a certain threshold value, accumulated spontaneous tracks in a mineral start fading. As a result, the track length as well as the track density decrease and consequently, the FT age determined for those minerals will be decreased as well.

One aspect of thermochronometric studies, which has significant potential but is

Department of Geosciences, Faculty of Science, Osaka City University.

*Presented at the 7th International Workshop on Fission Track Thermochronology, Philadelphia, July, 1992.

still sporadically exploited, is thermal history studies of mineral deposits. The space-time-temperature constraints of hydrothermal ore forming processes would aid not only scientific understanding of regional geology but would also be of considerable economic significance as well.

With these ideas in mind, we collected some samples from the Kanagase polymetallic ore vein of the Ikuno mining district and the dating was carried out by Fission Track method, using both internal and external surfaces of zircon.

2. Geologic Setting and Sampling

The Ikuno mining district is located in the central part of Hyogo prefecture and geologically belongs to the Inner zone of Southwest Japan (Fig. 1). The surrounding area consists of different kinds of rocks, ranged in age from Late Paleozoic to Quaternary (NAKAMURA, 1987). The ore bearing volcanic rocks of the Ikuno group (Late Cretaceous), acidic to intermediate in composition, occupy the main part of the stratigraphy column and are widely distributed in the area. The Ikuno group unconformably overlies the Late Paleozoic-Jurassic Maizuru group of volcano-sedimentary rocks and are covered by younger volcanic and volcanoclastic formations. A number of granitic bodies also intrude into the Ikuno group.

The Kanagase polymetallic ore vein, a very famous mine in the Ikuno ore field, is located within rhyolitic crystal welded tuff - a member of the Ikuno group. The mineralized zone along the vein has width 1 m~1.5 m, stretches for hundreds of meters and

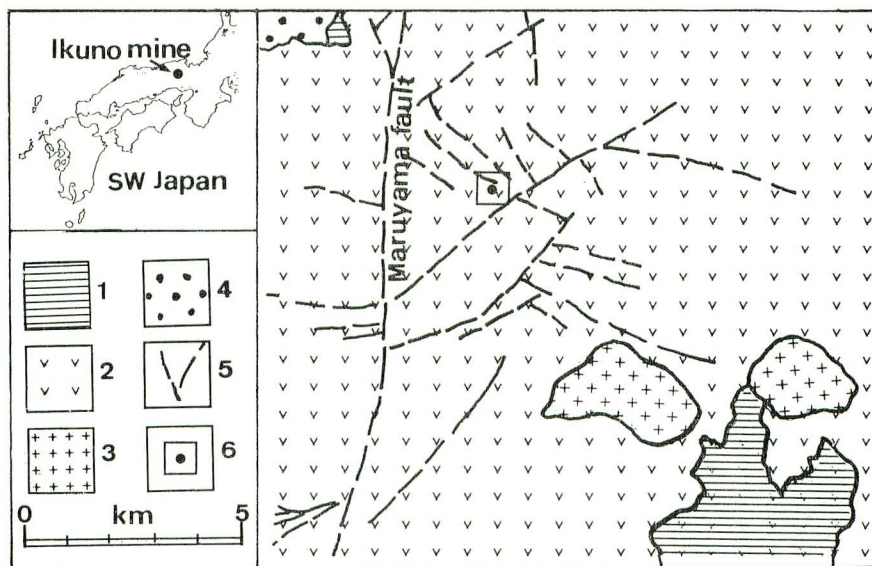


Fig. 1 Location of the study area and distribution of Ikuno group.

- 1) Maizuru group, 2) Ikuno group, 3) Creta-Paleogene granitic rocks, 4) Yakuno intrusive rocks, 5) Faults, 6) Ikuno mining area.

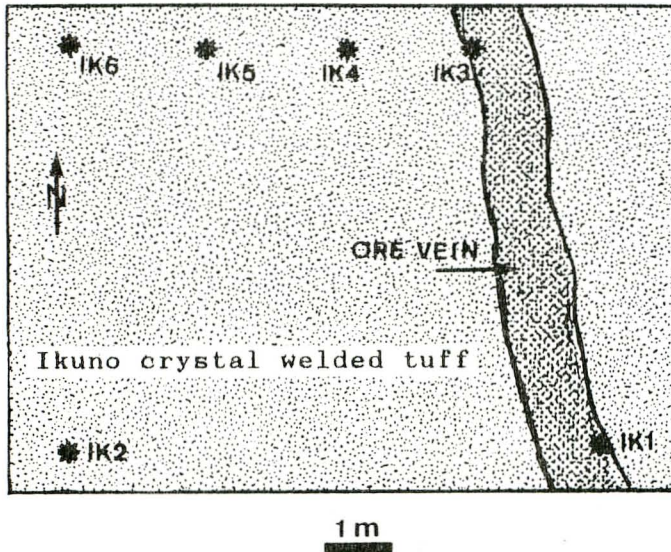


Fig. 2 Location of the sampling points at the Kanagase polymetallic ore vein.

has a vertical dip. The hydrothermal mineralization occurred in tension fractures and has polyascendent character. High-temperature and low-temperature minerals co-exist in the main part of the vein and the ore field as a whole.

During 1989 and 1990 we carried out a field survey in the Ikuno area and dated several zircon samples by FT method. The 2π FT ages obtained from the barren host rocks (IKU10, IKU20) was 99–108 Ma (Table 2).

In this study, the samples were collected in an orderly manner from the ore vein contact zone out into the host rocks as follows: IK1 and IK3–IK4–IK5–IK6–IK2, (Fig. 2). The distance between the samples along sampling route is about 2 meters.

3. Experimental Procedure and Result

3.1. Experimental procedure

Standard procedures for Fission Track Dating using External Detector Method (FTD-EDM) as described in published literature (FLEISCHER *et al.*, 1975; HURFORD and GREEN, 1982; TAGAMI *et al.*, 1988; DANHARA *et al.*, 1991) were adopted for the various steps of this study (Fig. 3). After the rock sample was crushed, sieved and panned, only euhedral zircon grains of each sample were picked by hand and mounted on two teflon sheets, one for 2π - and the other for 4π -geometry FT age determination. No chemicals or heavy liquids were used for zircon separation to avoid any uncertainties in further steps of the study.

The zircon samples for internal surface dating were etched in KOH:NaOH (1:1) at $225^{\circ}\text{C} \pm 1$ for 15 hours and then polished by diamond paste to expose 4π -geometry.

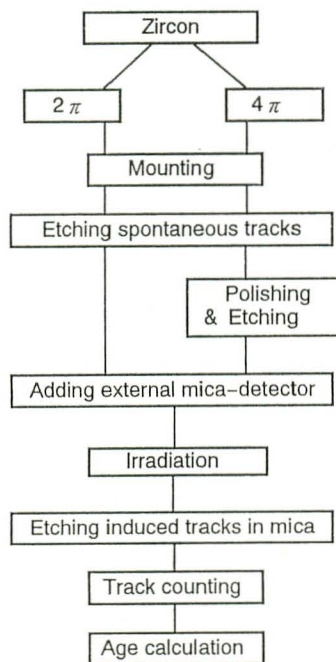


Fig. 3 Experimental procedure of Fission Track Dating using External Detector Method (FTD-EDM) applied for this study.

The same procedure was used with age standards, except that the etching time before polishing was 24 hours (Fish Canyon Tuff) and 28 hours (Buluk Tuff). Then all samples were etched by the same etchant with the same etching time as mentioned above for each kind of the samples. The initial etching before polishing was necessary to determine polishing sufficiency to reveal complete 4π -geometry surface of zircon. Incomplete polishing could yield underestimation of 4π track density and subsequent erroneous FT age calculation.

After etching mica detectors were attached to the zircon samples and to Dosimeter Glass (SRM 962a) and they were then irradiated at a pneumatic facility of the Kyoto University Reactor (KUR). The irradiation time was 30 sec. for the sample series of FCT 89 and IKU20; 60 sec. for the remained samples.

The mica detectors were etched in 47% HF at $25 \pm 1^\circ\text{C}$ for 20 min.

Counting of spontaneous and induced tracks was carried out using the Computerized Image-Processing System for Fission Track Dating (CIPS-FTD) (WADATSUMI *et al.*, 1988). The system can permanently preserve all of the data, from the unprocessed raw digital pictures to the final numerical results. The data can then be easily retrieved and verified at any time during the experimental procedure. To lessen the non-Poisson variation only the zircon grains with homogeneous track distribution were chosen for track counting.

3.2. Age calculation

FT age of the samples (T_{unk}) is obtained using the Zeta method proposed by Hurford and Green (1982, 1983):

$$T_{unk} = \frac{1}{\lambda_D} \ln \left[1 + \zeta \lambda_D g \frac{\rho_s}{\rho_i} \rho_d \right]$$

where λ_D is the total decay constant of U^{238} ; g is a geometry factor; ρ_s and ρ_i are spontaneous and induced fission track density of the sample, respectively; ρ_d is track density of Dosimeter Glass's mica detector; ζ is a calibration value that is calculated from age standards:

$$\zeta = \frac{(e^{\lambda_D T_{std}} - 1)}{\lambda_D g \left[\frac{\rho_s}{\rho_i} \right]_{std} \rho_d}$$

where T_{std} is the reference age of the standard sample.

The statistical error of zeta value (σ_ζ) and FT age (ρ_T) is given by (TAGAMI *et al.*, 1988):

Table 1 Age standard data for zeta value calibration to SRM 962a using external detector method.

Sample Code	Number of crystals	Spontaneous		Induced		Dosimeter (SRM 962a)		Zeta($\pm 1\sigma$)
		<i>Ps</i>	(<i>Ns</i>)	<i>Pi</i>	(<i>Ni</i>)	<i>Pd</i>	(<i>Nd</i>)	
FISH CANYON TUFF								
F91I	12	4.745	(710)	4.233	(635)	1.589	(2745)	315 \pm 18
F91E	12	3.952	(515)	6.453	(841)	1.589	(2745)	287 \pm 16
F92I	12	4.691	(643)	4.035	(553)	1.541	(3170)	312 \pm 18
F92E	10	3.959	(428)	6.040	(653)	1.541	(3170)	277 \pm 17
IKFI	9	4.388	(375)	4.224	(361)	1.556	(3508)	346 \pm 26
IKFE	10	3.848	(450)	5.738	(671)	1.556	(3508)	268 \pm 16
FCT90E	23	4.096	(853)	6.641	(1383)	1.623	(1531)	278 \pm 14
FCT89E	21	4.188	(769)	4.531	(832)	1.110	(1125)	274 \pm 15
BULUK TUFF								
BLKI	16	1.111	(371)	1.921	(642)	1.732	(1776)	324 \pm 22
BLKE	20	0.533	(236)	1.591	(705)	1.732	(1776)	280 \pm 22

- (1) ρ and N denote track density ($\times 10^6$ tr/cm²) and number of tracks, respectively.
- (2) F91, F92, IKF, FCT31, FCT32 and BLK are six irradiations carried out at the Kyoto University Reactor. The letters I and E of the sample code denote 4π and 2π zeta value calibration, respectively; $4\pi/2\pi$ geometry correction factor=0.5.
- (3) Ages of standard sample used are: Fish Canyon Tuff=27.9 \pm 0.7 Ma; Buluk Tuff=16.2 \pm 0.2 Ma.

Table 2 The FT age data of Kanagase samples using zeta calibration approach

Sample Code	Number of crystals	Spontaneous		Induced		Dosimeter (SRM 962a)		Age($\pm 1\sigma$)
		<i>Ps</i>	(<i>Ns</i>)	<i>Pi</i>	(<i>Ni</i>)	<i>Pd</i>	(<i>Nd</i>)	
IK1I IK1E	8	6.818	(486)	3.283	(234)	1.556	(3508)	55 \pm 4
IK2I IK2E	10 10	5.919 6.207	(662) (653)	2.548 3.365	(285) (354)	1.556 1.556	(3508) (3508)	62 \pm 4 76 \pm 5
IK3I IK3E	10 10	5.642 5.554	(573) (506)	2.737 2.512	(278) (228)	1.556 1.556	(3508) (3508)	55 \pm 4 91 \pm 7
IK5I IK5E	10 9	7.156 5.628	(696) (463)	3.177 3.015	(309) (248)	1.556 1.556	(3508) (3508)	60 \pm 4 77 \pm 6
IK6I IK6E	9 8	5.923 5.688	(583) (454)	2.632 2.882	(259) (230)	1.556 1.556	(3508) (3508)	60 \pm 4 81 \pm 6

IKU10E	9	6.606	(499)	2.965	(224)	1.632	(1531)	99 \pm 8

IKU20E	9	9.499	(818)	2.613	(225)	1.103	(1125)	108 \pm 8

- (1) ρ and N denote track density ($\times 10^{-6}$ tr/cm²) and number of tracks, respectively.
(2) The 4π and 2π FT ages denoted by letters I and E were calculated using separate 4π and 2π zeta values obtained from the age standard in each irradiation: 346 and 268 for sample series IK, 278 for IKU10 and 274 for IKU20 (Table 1); $4\pi/2\pi$ geometry correction factor=0.5.

$$\sigma_{\xi} = \zeta \sqrt{\left(\frac{\sigma_{Tstd}}{T_{std}}\right)^2 + \left[\frac{1}{N_s} + \frac{1}{N_i}\right]_{std} + \frac{1}{N_d}}$$

$$\sigma_{\tau} = T \sqrt{\frac{1}{N_s} + \frac{1}{N_i} + \frac{1}{N_d} + \left(\frac{\sigma_{\xi}}{\zeta}\right)^2}$$

where N_s and N_i are counted number of spontaneous and induced tracks, respectively; N_d is counted number of induced tracks of Dosimeter Glass; σ_{Tstd} is the error of the reference age of the standard.

The obtained zeta values and FT ages of the Kanagase samples are presented in Tables 1 and 2. In the Table 1, the 2π and 4π zeta values is seen different throughout six irradiations and for both Fish Canyon Tuff and Buluk Tuff. This could be resulted from the particular efficiency of (2π - and 4π -) track observation conditions, track identification and track counting. Therefore it is essential to calculate the 4π and 2π ages independently, using the respective 4π and 2π zeta value.

4. Discussion

In Fig. 4, the FT ages are plotted against sampling position. Two main tendencies are seen: first, the 4π ages tend to increase in age outward from the ore vein towards the

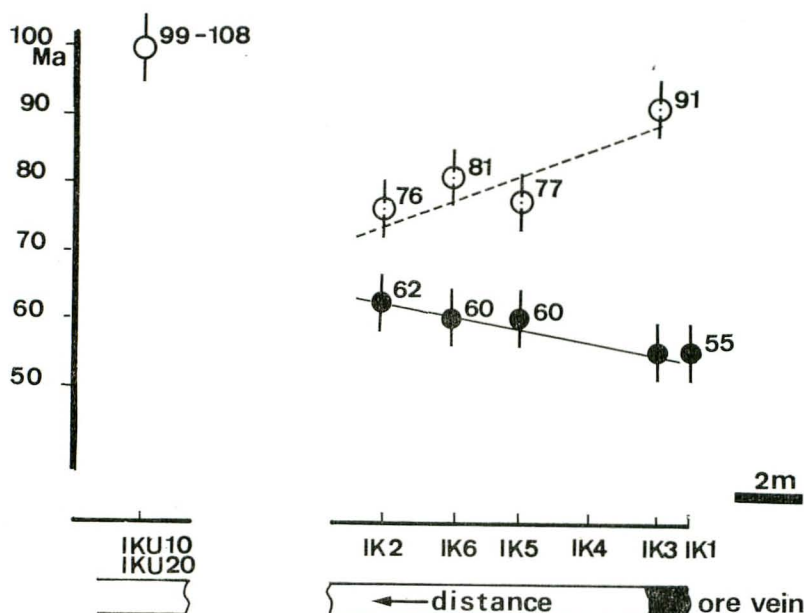


Fig. 4 Obtained FT ages are plotted against their sampling position. Solid circles show the ages for the 4π surface. The increase in age toward the contact zone could result from natural annealing by high temperature hydrothermal fluids during ore formation. The 2π ages marked by open circles, present an inverse trend of development. This is possibly due to complicated temporal and spatial combination of both natural etching and annealing (see corresponding discussion).

wallrocks and second, the 2π ages show an inverse character of development, i.e., the closer they are to the ore vein the older their ages become. As a result, the variation between 2π and 4π ages is gradually lessened from IK3 taken at the ore vein (91 vs 55 Ma) to the farthest IK2 (76 vs 62 Ma). Our field observation and the FT age data allow us to propose that the main factor for the FT age variation is the circulation of hydrothermal fluids that led to the formation of the Kanagase ore vein.

The amount of natural annealing is proportional to temperature and duration of time, but inversely proportional to distance from heat source (contact zone of intrusive or area of volcanic activity...). This is adequate to explain the trend of the 4π ages. This means that during the ore formation in the Kanagase area, the hydrothermal solutions may have reached temperatures sufficient to anneal spontaneous fission tracks, so that thermally affected zircons have younger apparent FT ages.

Before discussing the trend of the 2π ages mentioned above we think it is useful to consider some circumstances that may confuse the understanding of our proposed model for data interpretation.

Contrary to tracks inside zircon, the accumulation and behavior of spontaneous tracks on its surfaces may be strongly influenced by ambient conditions. Occasionally uranium enrichment surrounding a crystal surface (high uranium content in host rocks, uranium

“surface film” of zircon formed during late stage of granitic intrusive...) produces supplementary external spontaneous tracks. During sample processing this uranium source may be eliminated and expected induced tracks on mica detector may fail to be generated. This yields a higher N_s/N_i ratio and consequently an older apparent external surface FT age for the zircon grain compared with its internal one (SUZUKI *et al.*, 1988). Concerning the uranium content of host rocks and Kanagase ores, the following procedure has been adopted. A number of minerals from the ore and host rocks were mounted on a teflon sheet, after a mica detector was added, the mounts were subjected to irradiation similar to the zircon samples. No extra induced tracks were found in the mica detector. This experiment implies that no additional uranium has been brought in by hydrothermal mineralization. On the other hand, the regional geological and geochemical survey (NAKMAURA, 1987) allows to suggest that the host rocks - the crystal welded tuff member of the Ikuno group - formed in the conditions of strong heating of lavas and clastic materials. This led to complete fading of the initial spontaneous fission tracks in zircon crystals of the tuff member. Consequently, FT age of those zircons, regardless the sources they were brought from, should be reset to 0 at the time of the rocks formation.

The facts stated above enable us to use the ore forming process as the most probable mechanism leading to the 2π age distribution as shown in Fig. 4. This mechanism is discussed in detail below.

Hydrothermal alteration is characterized by reactions between hydrothermal fluids and the wallrocks in order to restore the physico-chemical equilibrium, which will be different under the new condition of pressure, temperature and chemical environment (BARNES, 1979). The hydrothermal solutions contain various active chemical reagents and are metasomatically enriched in ions (K^+ , Na^+ , H^+ , OH^- , F^- , SO_4^{--} ...), and therefore could act as natural etchant for fission tracks on zircon surface (Fig. 5).

The concept of natural etching should be understood merely as infiltration of natural chemicals into the damaged zone of external tracks rather than their enlargement during laboratory etching. Furthermore, the natural etching rate, which is proportional to temperature, time, and chemical composition of hydrothermal solutions determines both the number of etched tracks and etching degree. Tracks that have undergone natural etching would be strongly protected from annealing.

Thus, hydrothermal mineralization generates natural annealing and natural etching to the tracks on zircon crystal surfaces, whereas tracks inside a crystal may be influenced by natural annealing only. Moreover, under actual geological conditions this combined effect is not constant.

According to MARUYAMA (1957, 1959) and NAKAMURA (1971, 1991), the ore vein mineralization has polyascendent character and overgrowths of high temperature and low temperature minerals are seen at the Kanagase vein. That means the hydrothermal fluids - carrier of heat and ore materials on the way upwards from the source - caused alteration and deposition of low temperature minerals and then reached higher temperature stage. Therefore at different depth level the following order of mineralization stages and ac-

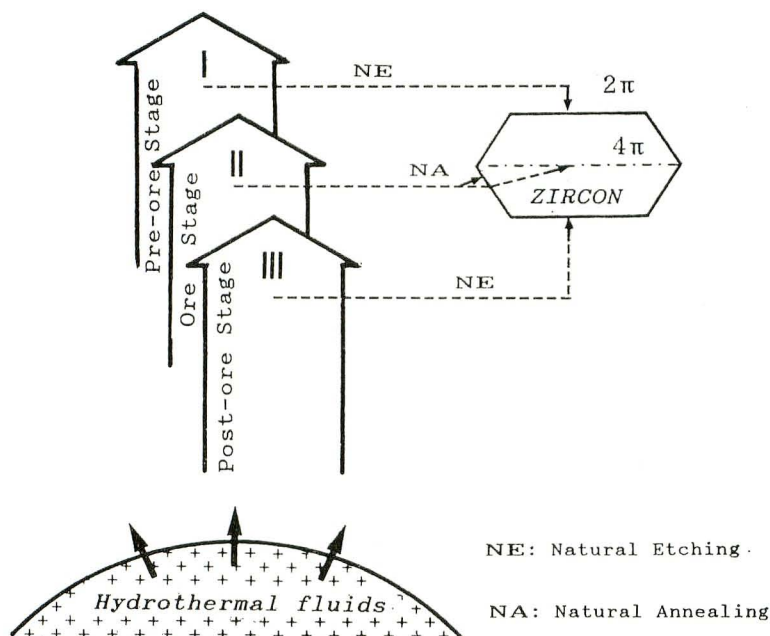
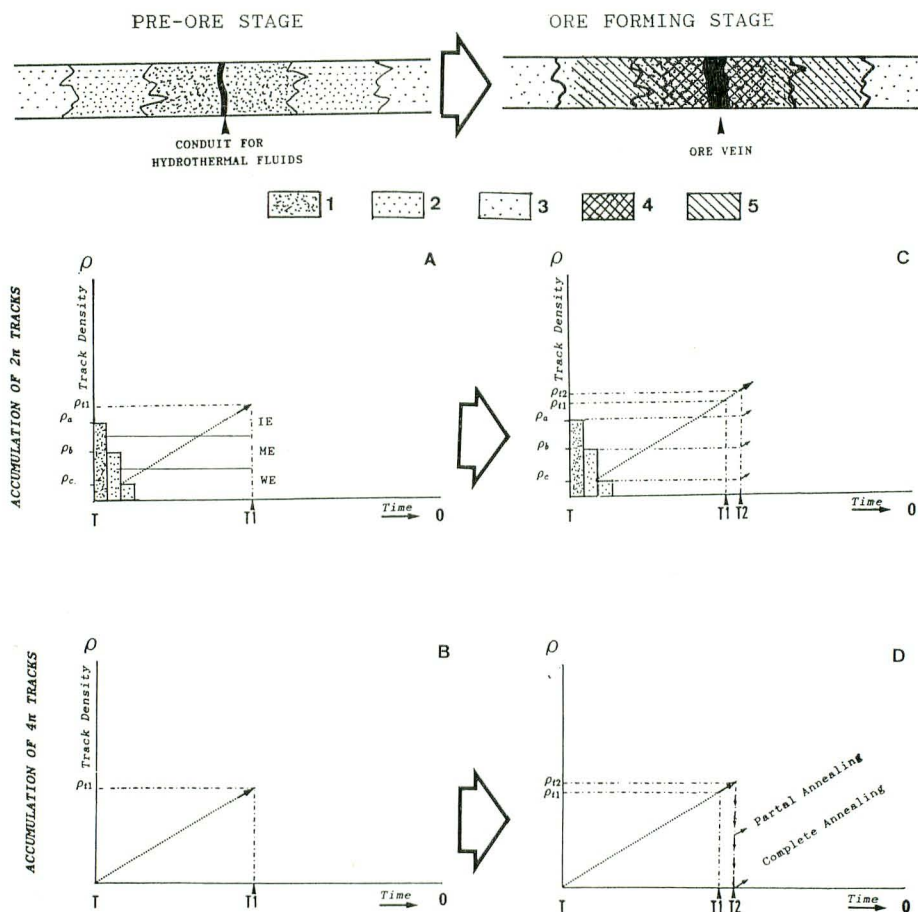


Fig. 5 Evolution of hydrothermal ore forming process and its effect on fission track age of the Kanagase samples. I. Pre-ore alteration stage. Hydrothermal fluids containing various active chemical reagents (H^+ , Cl^- , K^+ , Na^+ , SO_4^{--} , OH^- ...) became natural etchant for 2π tracks. II. Ore-forming stage with high temperature could cause natural annealing to 2π and 4π tracks. III. Post-ore stage, as the last low temperature ore deposition and alteration, could yield etching of the tracks on crystal surfaces. 4π FT age of the samples subjected to hydrothermal mineralization may reflect the annealing environment, whereas 2π FT age is considered due to the combined effect of both natural etching and annealing.

companied natural etching and annealing can be observed (Fig. 5): I. Low temperature pre-ore alteration stage with etching phenomena; II. High temperature ore forming stage mainly involving annealing; III. Low temperature post-ore stage without significant effect on FT age.

Pre-ore alteration stage

This stage is considered as initial alteration caused by hydrothermal fluids around the conduit. The alteration zones underwent a stepwise expansion corresponding with each new pulse of hydrothermal fluids. As a result, from the conduit outward there are three zones of alteration and natural etching of external spontaneous tracks; namely, intensive, moderate and weak zones. The density of 2π and 4π tracks remained the same during this initial, relatively low temperature stage. However, the tracks on zircon surface included a number of partially etched tracks. These etched tracks could continue existing even if non-etched tracks might be naturally annealed in the next high temperature stage (Fig. 6 A, B).



Etching zones: 1) intensive, 2) moderate, 3) weak; Annealing zones: 4) complete, 5) partial
Fig. 6 Behavior of fission tracks during hydrothermal mineralization.

Pre-ore alteration stage at time T_1 :

A) Natural etching zones from the contact of hydrothermal fluids outward: intensive etching (IE), moderate etching (ME), and weak etching (WE) with decreasing number of naturally etched 2π tracks (ρ_a , ρ_b , ρ_c).

B) 4π tracks remained unaffected due to low temperature of this stage.

Ore forming stage at time T_2 :

C) The previously etched zircons are affected by succeeding natural annealing. Under the conditions of complete annealing number of 2π tracks (ρ_a , ρ_b , ρ_c) could survive.

D) 4π tracks may be totally or partially erased, depending on annealing intensity.

Thus, apparent 4π and 2π FT ages vary from one sample to another and 4π & 2π ages of the same zircons may also be different due to concrete conditions. In the case of complete annealing the 4π age records the time of the ore forming stage.

Ore-forming stage

In this discussion, the time when the solutions reached the annealing temperature is

regarded as approximately the start of ore forming stage. The Kanagase polymetallic ore vein consists of various ore mineral associations, which formed in several phases. Since the duration of mineralization is fairly short compared with the age of the host rocks, we assign all these phases to one stage, focusing on the idea that this stage yielded both natural annealing and etching by high temperature hydrothermal fluids. Under the same conditions external and internal tracks would behave in different ways. We consider some typical cases separately.

4π -geometry tracks

Depending on distance from the heat source the following zones of different annealing rate can be observed: complete, partial and non-affected (Fig. 6 D). In the case of complete annealing, the FT age reflects the age of the ore forming stage, assuming that the area has not subjected to any subsequent thermal events. In the partial annealing zone the apparent 4π FT age lies between the age of the host rocks and the age of the ore formation.

The apparent 4π ages of the Kanagase samples represent an orderly weakening influence by annealing outward from the ore vein: IK1 & IK3 (55 Ma) → IK5 & IK6 (60 Ma) → IK2 (62 Ma).

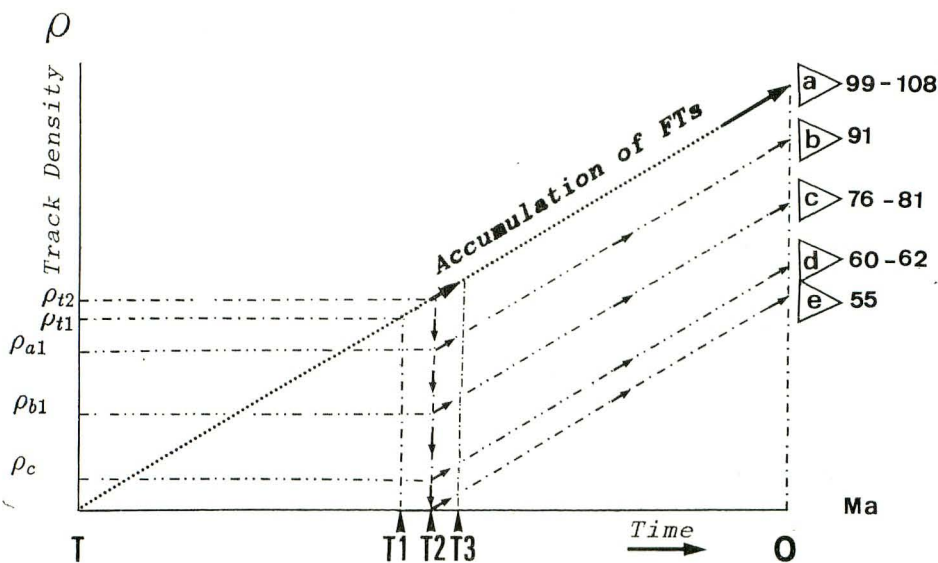


Fig. 7 Graphic illustration of the FT ages of Kanagase asmples. a) 2π age of the barren host rocks; b) 2π age of the sample strongly naturally etched prior annealing (IK3); c) 2π age caused by combined etching and annealing (IK5, IK6, IK2); d) 4π age of the partially annealed samples (IK 5, IK6, IK2); e) 4π age of the strongly annealed samples (IK1, IK3). T1, T2 are the starting time of etching and annealing, respectively; T3 is the time of the post ore alteration stage, which caused no significant effect on FT age.

2 π -geometry tracks

Under the condition, for example, of complete annealing when the 4 π tracks and non-etched 2 π tracks might be erased completely, the external zircon crystal surface will still maintain a certain number of tracks, which were previously naturally etched (Fig. 6 C). The 2 π ages showed in Table 2 and Figure 4 seem to be concordant with the proposed natural etching rate. The oldest 2 π FT age of 91 Ma (IK3), occurs despite of the strong annealing conditions reflected by its youngest 4 π FT age (55 Ma). This demonstrates that significant natural etching occurred before annealing at the contact zone of the ore vein. The reduction of the 2 π age of IK3 is smallest compared with the unaffected 2 π ages dated previously (99–108 Ma).

Further away from the contact zone both etching and annealing effects generally decrease. This trend can be seen by comparing the pair of 2 π and 4 π ages of each sample IK5, IK6 and IK2: 77–60 Ma, 81–60 Ma, 76–62 Ma, respectively. At a certain distance from the ore vein natural etching disappears and both FT ages (2 π and 4 π) should merge and have the same mode of development (Fig. 8).

Post-ore stage:

Fluid inclusion analysis of the samples from Kanagase ore vein was done at the Institute of Geology, Buriatian Branch, Academy of Sciences, Russia. The data showed that the homogenization temperatures of inclusions in secondary minerals formed along

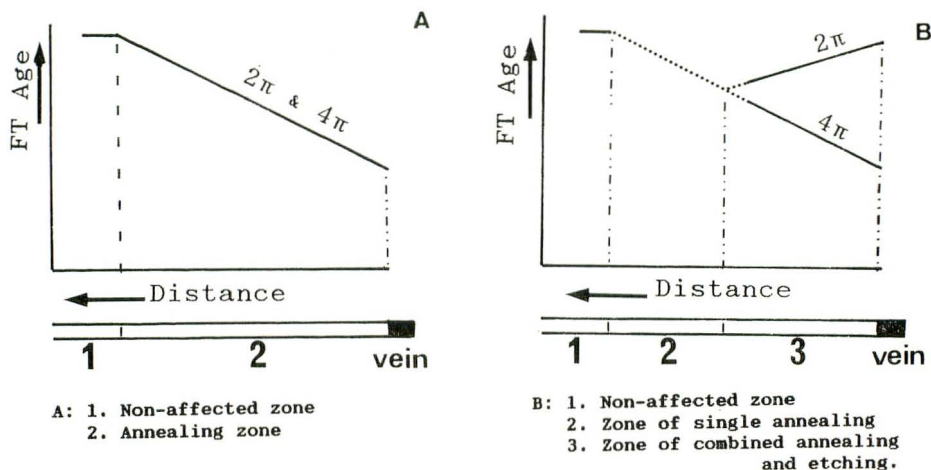


Fig. 8 Principal development of fission track age under the condition of single natural annealing (A) and of combined effect of natural etching and annealing (B). In both cases 4 π age, which is influenced by only annealing rejuvenates in the direction toward the contact zone. The 2 π tracks subjected to previous natural etching for a definite distance from the contact zone prove the stronger resistance to annealing. Consequently, for the same sample apparent 2 π age is older than 4 π one. This 4 π -2 π age variation is decreasing faraway from the contact zone and the two ages merge when the etching effect disappears. The second concept (B) is applicable to the Kanagase samples.

the microfissures of sphalerite crystals is estimated at 105–145°C. At this temperature neither internal nor external tracks in zircon would be annealed.

The K-Ar age of pre-ore rhyolitic dikes - 72.8 Ma was reported by ISHIHARA and SHIBATA (1972) and 77 Ma for granodiorite intrusion in southern part of the study area by IMAI *et al.*, (1970). The internal surface FT age of IK1 and IK3 (55 Ma) is the youngest age obtained for samples from the Ikuno mining area. This FT age, if it is the result of complete annealing can be used to estimate the ore forming age. This suggestion needs some further studies, especially the measurement of track length. It also gives an argument to consider the sources and timing of ore deposition in the region (UTADA, 1980). The other age data are regarded to have been generated from the above discussed mixed annealing and etching during the Kanagase ore vein formation (Fig. 7).

Various spatio-temporal relations and the intensity of the natural etching and annealing make the proposed model more complicated. Nevertheless this model is practically adequate to explain the obtained FT ages, taking into consideration the effect of hydrothermal activity in the Kanagase ore field.

Recent works of some investigators have also suggested the difference in thermal stabilities of the 2π and 4π tracks and the ages determined by the two surfaces. The result of the present study, which is dedicated to application of fission track analysis for thermal history of ore forming process, suggests that care should be used prior to geological interpretation of fission track ages obtained from external zircon surfaces.

Acknowledgement

The first author (N.V.K.) wishes to express his sincere thanks to the Ministry of Education, Science and Culture, Japanese Government for the award of the Monbusho Scholarship. Thanks are also due to Associate Professor K. SHIONO and Dr. S. MASUMOTO of the Osaka City University for their encouragement. The first author (N.V.K.) thanks his colleagues at the Osaka City University, SAKAMOTO M., VENKATESH R. and KITADA N. for their help. We are grateful to Emeritus Prof. T. NAKAMURA for his valuable suggestions. The comments received from Prof. K. MATSUDA (Himeji Institute of Technology) and Dr. B.J. KOWALLIS (Brigham Young University, USA), which has improved the quality of this manuscript, is thankfully acknowledged.

References

- BARNES, H.L. (1979): Geochemistry of hydrothermal ore deposits, John Wiley and Sons, New York, pp. 176–235.
- Catalog of NBS Standard Reference Materials (1984), NBS Spec. Publ. p. 260.
- DANHARA, T. *et al.*, (1991): Fission-track age calibration using internal and external surfaces of zircon. Jour. Geo. Soc. Japan, 97, pp. 977–985.
- FLEISCHER R.L., PRICE, P.B. and WALKER, R.M. (1975): Nuclear Tracks in Solids: Principles and Applications, Univ. of California Press, Berkeley, Calif.
- HURFORD, A.J. and GREEN, P.F. (1982), A User's Guide to Fission Track Dating Calibration,

- Earth and Planet. Sc. Letters, 59, Elsevier Publ. Comp., Amsterdam, pp. 343–354.
- HURFORD, A.J. and GREEN, P.F., (1983): The zeta age calibration of fission track dating. *Isotope Geosc.*, 1, 285–317.
- IMAI, H. *et al.*, (1970): Geology and mineral deposits of Akenobe mine and the Ningyo-toge uranium deposit. IMA-IAGOD Tokyo-Kyoto Meeting, Guidebook 8, pp. 1–48.
- ISHIHARA, S. and SJIBATA, K., (1973): Re-examination of the Metallogenic Epoch of the Ikuno-Akenobe Province in Japan. *Min. Geol.* 22, pp. 67–73.
- MARUYAMA, S., (1957): The relation between ore veins and igneous intrusives at the Ikuno mine, *Mining Geol.*, 7, pp. 281–284. (In Japanese with English abstract)
- MARUYAMA, S., (1959): Zonal distribution of ore deposit and prospecting at Ikuno mine, *Mining Metall. Inst. Japan Jour.*, v. 75, pp. 673–677. (In Japanese)
- MATSUDA, T., (1991): Annealing character of fission tracks in zircon: comparison between internal and external surfaces. *Abst. 98th Ann. Meeting Geol. Soc. Japan*, p. 457. (In Japanese).
- NAKAMURA, T., (1971): Mineral zoning as related to intersecting structures of fractures in the subvolcanic hydrothermal polymetallic vein-type deposits in Japan, *Mining Geol. Spec. Issue*, 37, Tokyo Japan, pp. 47–51.
- NAKAMURA, T. *et al.*, (1987): Report on Regional Geo-structural Survey in Bantan Area. Agency for Natural Energy, Ministry of Industry and Trading of Japan, p. 178. (In Japanese)
- NAKAMURA, T., (1991): Significant geologic and metallogenic features of polymetallic vein deposits in Japan, *Global Tectonic and Metallogeny*, Vol. 3, No. 4, pp. 213–220.
- SUZUMI, K., (1988): Heterogeneous distribution of uranium within zircon grains: Implication for fission track dating. *Jour. Geo. Soc. Japan*, 94, pp. 1–10.
- TAGAMI, T. *et al.*, (1988): Fission Track Dating Using External Detector Method: a Laboratory Procedure, *Mem. of Fac. Sc. Kyoto Univ., Series of Geol. & Min.*, Vol. LII, Kyoto Japan, pp. 1–30.
- UTADA, M., (1980): Hydrothermal alteration related to igneous activity in Cretaceous and Neogene formation of Japan, "Granitic magmatism and related mineralization", *Mining Geol. Spec. Issue*, 8, Tokyo Japan, pp. 67–83.
- WADATSUMI, K., MASUMOTO, S. and SUZUMI K., (1988): Computerized Image-Processing System for Fission Track Dating (CIPS-FTD), *Jour. Geosc.*, 31, Osaka City Univ., Japan, pp. 19–46.
- WAGNER, G.A., (1981b): Fission Track Ages and Their geological Interpretation, *Nucl. Tracks*, 5, Pergamon Press, pp. 15–25.